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14. ABSTRACT

The objectives of this study were to detail the fundamental physical processes that occur in rotor/turbulence interaction to aid the development of inflow turbulence modeling and turbulence ingestion noise prediction tools. In addition, a significant goal of this project was to conduct and document detailed flow and noise measurements needed to validate computational models of this interaction. Two experimental arrangements were investigated considering ingestion of a planar turbulent boundary layer and the wake shed by an upstream cylinder. It was found that with increasing thrust turbulence distortion effects were greater in the boundary layer arrangement due to increased stretching of turbulence caused by the impermeable wall boundary condition. This produced prominent haystacking peaks about the blade passage frequency (BPF) and its harmonics. Also, at low advance ratios, a separation region would develop on the wall that increased the noise at harmonics of the BPF as well. In the wake ingestion case, distortion was less important. The directivity of the turbulence interaction source and its strength was found to be a function of the proportion of the rotor disk area immersed in the turbulent field and its distribution across the rotor disk area.

15. SUBJECT TERMS

Aeroacoustics, hydroacoustics, turbulence ingestion, rotor noise

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Advancing Analytical and LES-Based Predictions Of Turbulence Ingestion Noise in Complex Environments – An Experimental Study

Final Technical Report to the Office of Naval Research
(Technical Monitors: Ki-Han Kim and John Muench)

Grant N00014-14-1-0141 / N00014-16-1-2395

William J. Devenport and W. Nathan Alexander
September 2017

This final technical report summarizes work conducted for the above grant during the period January 1, 2014 until June 30, 2017. This project is concerned with the noise generated by the ingestion of turbulence into a rotor. The process of ingestion distorts the turbulence and results in the generation of new turbulent structures that interact with the rotor blades generating unsteady lift and radiating sound. This process is considerably complicated by the fact that, in almost all practical situations, the turbulence ingested is inhomogeneous and anisotropic and thus both mathematically and physically complex. Furthermore, in many situations, the turbulence exists in a non-uniform mean flow bounded by nearby structures, such as a vehicle hull, that further complicate the interaction.

The over-arching goal of this work is to tackle the turbulence ingestion noise (TIN) problem in a carefully controlled scientific fashion that leads to the development of prediction methods that allow the fluid dynamics and acoustics to be more accurately accounted for in the analysis and design of vehicles and vehicle systems. Specifically, our goals have been

a) to reveal the fundamental physical processes that occur and thus provide the basis for analytical and semi-analytical models for the prediction of turbulence ingestion noise and of the turbulent processes involved,
b) to provide precise quantitative measurements of TIN and the associated fluid dynamics suitable for the validation of high fidelity computational models such as Large Eddy Simulation (LES).

Reflecting these goals, the experimental work performed under this project has being conducted in close collaboration with parallel ONR sponsored efforts. Specifically, analytical studies of TIN being conducted at Florida Atlantic University under the direction of Prof. Stewart Glegg, and computational studies (using LES) of TIN being performed at the University of Notre Dame under the leadership of Prof. Meng Wang.

Experimental studies have focused on two different configurations. The first configuration studied in this project is the ingestion of an otherwise two dimensional, equilibrium turbulent boundary layer growing over a plane wall into an idealized unshrouded rotor. Work performed on this configuration was a direct extension of prior studies performed under N00014-10-1-0908. The rotor is a scaled-up 225% replica of the design used by Maurice Sevik in 1973 (International Symposium on Fluid Mechanics and Design of Turbomachinery, University Park, Pennsylvania) to make some of the first measurements of rotor turbulence ingestion. It has a simple, generic, geometry including 10 constant chord blades with no skew or lean. The two-dimensional turbulent boundary layer was also chosen for its relative simplicity. With the slow rate of boundary layer growth this flow has mean velocity and turbulence fields that essentially vary only in one direction – that perpendicular to the wall. Likewise, the two-point correlation structure of its turbulence, which defines the full linear inflow boundary condition to the rotor, is reduced to a four-dimensional tensor function of distance from the wall and separation in the spanwise, wall normal and streamwise (or time-wise) directions. The experiments performed in this project (as opposed to its predecessor) focused PIV measurements of the rotor boundary layer interaction, as well as studies of the effects of rotor yaw both on the rotor sound field and turbulence structure of the interaction. Measurements were made over a broad range of advance ratios, from braking to highly thrusting, and as a function of rotor yaw angle which was varied from -15 to 15 degrees. The noise radiated from the rotor is dominated by haystacking peaks at multiples of the blade passing frequency. These broadband features result from the multiple cutting of turbulent eddies by successive blades of the rotor, and thus blade-to-blade correlations in the unsteady upwash experienced by the blades and the unsteady lift they produce. At low and moderate thrust, it was found, among other things, that the radiated turbulence ingestion noise is closely consistent with the space-time correlation properties of the undisturbed boundary layer and the distortion associated with the acceleration of the flow into the rotor disk. Trailing edge noise, radiated from portions of the blade disk outside of the boundary layer, was also observed. At high thrust, however, the flow visualizations and PIV measurements revealed the formation of a highly unsteady region of flow separation from the wall under the rotor disk, with a form highly dependent on yaw angle. At the same time, amplification and narrowing of the haystacking peaks was observed as well as their propagation to higher harmonics. Analysis of instantaneous vortical structures in the separation region showed asymmetries in the sign of eddies developed near the wall. Eddies with a sign of rotation consistent with the circulation of the blades were found more often, consistent with them being trailing structures shed from the blade tips. The organization of these structures was further biased by yaw, which was found to diminish the intensity of the separation. Analysis of the spectral peaks in the radiated noise and of the frequency and strength of organized eddies in the vicinity of the blade tips strongly suggested that the former were generated by blade vortex interaction. The combination of extensive PIV data, the far-field noise measurements and parallel analysis performed at FAU has provided for the first time a very detailed view of the turbulent flow physics and noise generation processes associated with what is generally known as propeller hull interaction.

The second configuration studied in this project has been that of the ingestion of a planar cylinder wake into the same Sevik rotor. This configuration was chosen so that the effects of advance ratio could be studied without the complication of an adjacent wall boundary condition, and to provide a simulation test case that would not require the computational modeling of surfaces in relative motion. The cylinder was placed 20 diameters upstream of the rotor and had a diameter $1/9^{th}$ of the diameter of the rotor disk. As with the turbulent boundary layer, complete measurements of the 4-dimensional space time correlation tensor of the wake were made at the rotor location but with the rotor removed. These measurements fully define the linear inflow boundary condition to the rotor. Wind tunnel tests were performed to study the sound generated by the ingestion of the wake, as well as the unsteady upwash correlations on the blades producing the sound, as functions of advance ratio and rotor yaw. Sound measurements were made with a new ONR-DURIP funded 251-microphone phased array in two configurations. In the first configuration the array, installed as a single unit, the array was used to document the continuous directivity map of the rotor sound field for a wide range of sideline angles. In the second configuration, the array was split into two halves which were sampled simultaneously from both sides of the test section to provide beamform maps of the source distribution over the rotor disk.

This configuration has been a productive source of new science and understanding in the field of microphone arrays.

This work has established a number of important new findings. Firstly, for example, wake ingestion produces much less distinct haystacking than boundary layer ingestion. There are several reasons here; the stretching and distortion of the turbulence entering the rotor is reduced when it is not adjacent to a wall; wakes have larger lateral scales than turbulent boundary layers of similar scale, reducing the number of haystack harmonics; and the upsweep and down sweep of the blades on opposite sides of the rotor disk oppositely bias their interactions with ingested turbulence, broadening the spectral peaks associated with those interactions. Secondly, the rotor ingesting the wake generates a sound field with a dipole-like directivity oriented perpendicular to the blade chord at the regions(s) where blades cut the highest turbulence. As such, the primary effect of yaw is to re-orient the sound field with the rotor. This changes the effective directivity angles of fixed microphone instrumentation, changing the apparent sound field. Thirdly, the primary effects of moving the wake strike location across the rotor disk is to change the sound level according to the degree of immersion of the rotor, and to shift the region of strongest sound production to the area(s) where the outer portion of the rotor is cutting the highest intensity turbulence. For a two-dimensional wake striking the centerline of the rotor, this places sources towards the top and bottom of the rotor disk. For a port or starboard strike, this shifts the dominant source locations towards those sides of the disk. Finally, rotor frame measurements show the wake necking down and being dragged toward the rotor center at high thrust. Blade to blade coherence is greater at low frequencies and less at high frequencies than the TBL due to differences in spanwise turbulence correlation

An independent theme and secondary effort of this project has been to investigate trailing edge noise control for rotors, in the absence of inflow turbulence, using trailing edge boundary layer modification devices known as finlets (Clark *et al.* AIAA Journal, 2017, vol. 55, no. 3, pp. 740-754). This component of the project follows on from work conducted under N00014-15-1-2721. The finlets are small, closely spaced, fins or rails projecting from a lifting surface just upstream of the trailing edge. Inspired by anatomical features of silent flying owls, the finlets are designed to break up the boundary layer turbulence and displace it away from the trailing edge. These devices have been demonstrated to produce over 10dB of noise reduction over a broad frequency range on static airfoils. For this portion of the project, a large-chord 457-mm diameter two-bladed rotor system for trailing edge noise study was developed, based on a marine propeller. Finlets based on the most successful designs used for static airfoils were developed and adapted to the curved blade surfaces using CFD calculations to determine likely streamline directions. Phased array measurements of the rotor far field sound, over a range of blade angles of attack (i.e. advance ratios), were made with the blades both tripped and untripped. Results indicated that closely-spaced finlets were effective at reducing both trailing edge noise and vortex shedding noise due to the blunt trailing edges of the blades. Widely spaced finlets were less effective. Noise predictions using the methods of Brooks, Pope, and Marcolini (NASA RP1218) revealed the frequency ranges where each source of noise was dominant. Velocity and turbulence measurements made in the near wakes of the treated and untreated rotor blades showed that the mechanism for noise reduction was likely similar to the noise reduction mechanism observed with static airfoils, namely the displacement of turbulence away from the immediate vicinity of the trailing edge and the reduction of the spanwise correlation length scale.

Details of the above experiments, the measurements made, the analysis of results and the formulation of findings can be found in the theses and articles published over the course of this project, listed below. Note also that the experimental data from the boundary layer study has been adopted as test case FC3 for the AIAA Broadband Rotor Noise Workshop.

Publications

Degrees

1. Clark, I. (2017), Bio-Inspired Control of Roughness and Trailing Edge Noise, PhD Dissertation, Virginia Tech.
2. Molinaro, N.J. (2017), The Two Point Correlation Structure of a Cylinder Wake, MS Thesis, Virginia Tech
3. Murray, H. (2016). Turbulence and Sound Generated by a Rotor Operating Near a Wall, MS Thesis, Virginia Tech.
4. Wisda, D. (2015). Noise from a Rotor Ingesting Inhomogeneous Turbulence. MS Thesis, Virginia Tech

Journal Papers

5. Alexander, W. N., Devenport, W. J., and Glegg, S. A., 2017, "Noise from a Rotor Ingesting a Thick Boundary Layer and Relation to Measurements of Ingested Turbulence", *Journal of Sound and Vibration, 2017. **409**: p. 227-240.*
6. Henry H. Murray, W. Nathan Alexander, William J. Devenport, Stewart A. L. Glegg, David Wisda, 2017, "Aeroacoustics of a Rotor Ingesting a Planar Boundary Layer at High Thrust", under review, *Journal of Fluid Mechanics*.
7. Glegg, S.A.L., W. Devenport, and N. Alexander, Broadband rotor noise predictions using a time domain approach. *Journal of Sound and Vibration*, 2015. **335**: p. 115-124.

Textbook

8. Glegg, S., and Devenport, W., *Aeroacoustics of Low Mach Number Flows: Fundamentals, Analysis, and Measurement*: Elsevier Science, 2017.

Conference Papers

9. Molinaro N, Hickling C, Alexander N, Devenport W and Glegg S, 2017, "The Ingestion of Wake Turbulence into an Open Rotor", 23rd AIAA/CEAS Aeroacoustics Meeting, Denver CO. 5-9 June.
10. Hickling C, Alexander N, Molinaro N, Devenport W and Glegg S, 2017, "Efficient Beamforming Techniques for Investigating Turbulence Ingestion Noise with an Inhomogeneous Inflow ", 23rd AIAA/CEAS Aeroacoustics Meeting, Denver CO. 5-9 June.
11. Clark, I., Alexander W. N. and Devenport W. J., 2017. Bio-Inspired Finlets for the Reduction of Marine Rotor Noise. AIAA Aviation 17. Denver CO.
12. Glegg, S., Grant, J., Alexander, N., and Devenport, W., "Sound Radiation from a Rotor Operating in the Wake of a Cylinder," in 55th AIAA Aerospace Sciences Meeting, Grapevine, TX, 2017.
13. Alexander, N., N. J. Molinaro, C. Hickling, H. Murray, W. Devenport and S. Glegg (2016). Phased Array Measurements of a Rotor Ingesting a Turbulent Shear Flow. 22nd AIAA/CEAS Aeroacoustics Conference. Lyon, France.

14. Glegg, S., J. Grant, D. Wisda, H. Murray, N. Alexander and W. Devenport (2016). Broadband Noise from a Rotor at an Angle to the Mean Flow. AIAA Scitech 2016. San Deigo, CA.
15. Glegg, S., J. Grant, H. Murray, W. Devenport and N. Alexander (2016). Sound Radiation from a Rotor Operating at High Thrust Near a Wall. 22nd AIAA/CEAS Aeroacoustics Conference. Lyon, France.
16. Wisda, D., H. Murray, N. Alexander, M. A. Nelson, W. J. Devenport and S. Glegg (2015). Flow Distortion and Noise Produced by a Thrusting Rotor Ingesting a Planar Turbulent Boundary Layer. Aviation 2015. Dallas, TX..
17. Murray, H., D. Wisda, N. Alexander, M. A. Nelson, W. J. Devenport and S. Glegg (2015). Sound and Distortion Produced by a Braking Rotor Operating in a Planar Boundary Layer with Application to Wind Turbines. Aviation 2015. Dallas, TX.
18. Glegg, S., A. Buono, J. Grant, F. Lachowski, W. Devenport and N. Alexander (2015). Sound Radiation from a Rotor Partially Immersed in a Turbulent Boundary Layer. Aviation 2015. Dallas, TX.
19. Alexander, W. N., Devenport, W. J., Wisda, D., Morton, M. A. and Glegg, S. A., 2014, "Sound Radiated from a Rotor and Its Relation to Rotating Frame Measurements of Ingested Turbulence", 20th AIAA/CEAS Aeroacoustics Conference, Atlanta, GA, 16-20 June. AIAA 2014-2746
20. Wisda, D., Alexander, W. N., Devenport, W. J. and Glegg, S. A., 2014, "Boundary Layer Ingestion Noise and Turbulence Scale Analysis at High and Low Advance Ratios", 20th AIAA/CEAS Aeroacoustics Conference, Atlanta GA, 16-20 June. AIAA 2014-2608